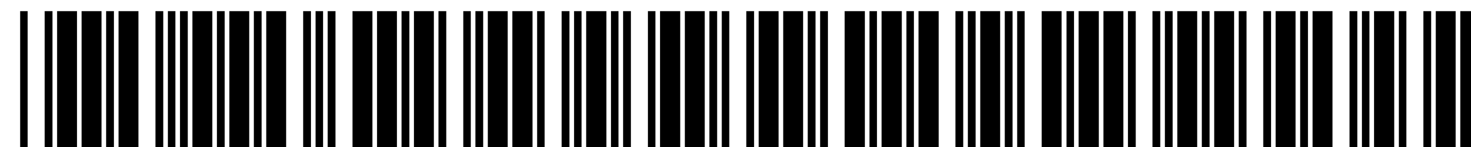
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Hu et al.

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(45) **Date of Patent: *Oct. 3, 2023**

(54) **LINE EDGE ROUGHNESS ANALYSIS USING ATOMIC FORCE MICROSCOPY**

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(Continued)

(51) **Int. Cl.**

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G01Q 60/24 (2010.01)

(52) **U.S. Cl.**

CPC ***G01B 21/30*** (2013.01); ***G01Q 60/24*** (2013.01)

(58) **Field of Classification Search**

CPC G01B 21/30; G01Q 60/24
See application file for complete search history.

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(57) **ABSTRACT**

Embodiments disclosed herein relate generally to methods for measuring a characteristic of a substrate. In an embodiment, the method includes scanning over the substrate with a scanning probe microscope, the substrate having fins thereon, the scanning obtaining images showing respective fin top regions of the fins, the scanning probe microscope interacting with respective portions of sidewalls of the fins by a scanning probe oscillated during the scanning, selecting images obtained at a predetermined depth below the fin top regions to obtain a line edge profile of the fins, by a processor-based system, analyzing the line edge profile of the fins using power spectral density (PSD) method to obtain spatial frequency data of the line edge profile of the fins, and

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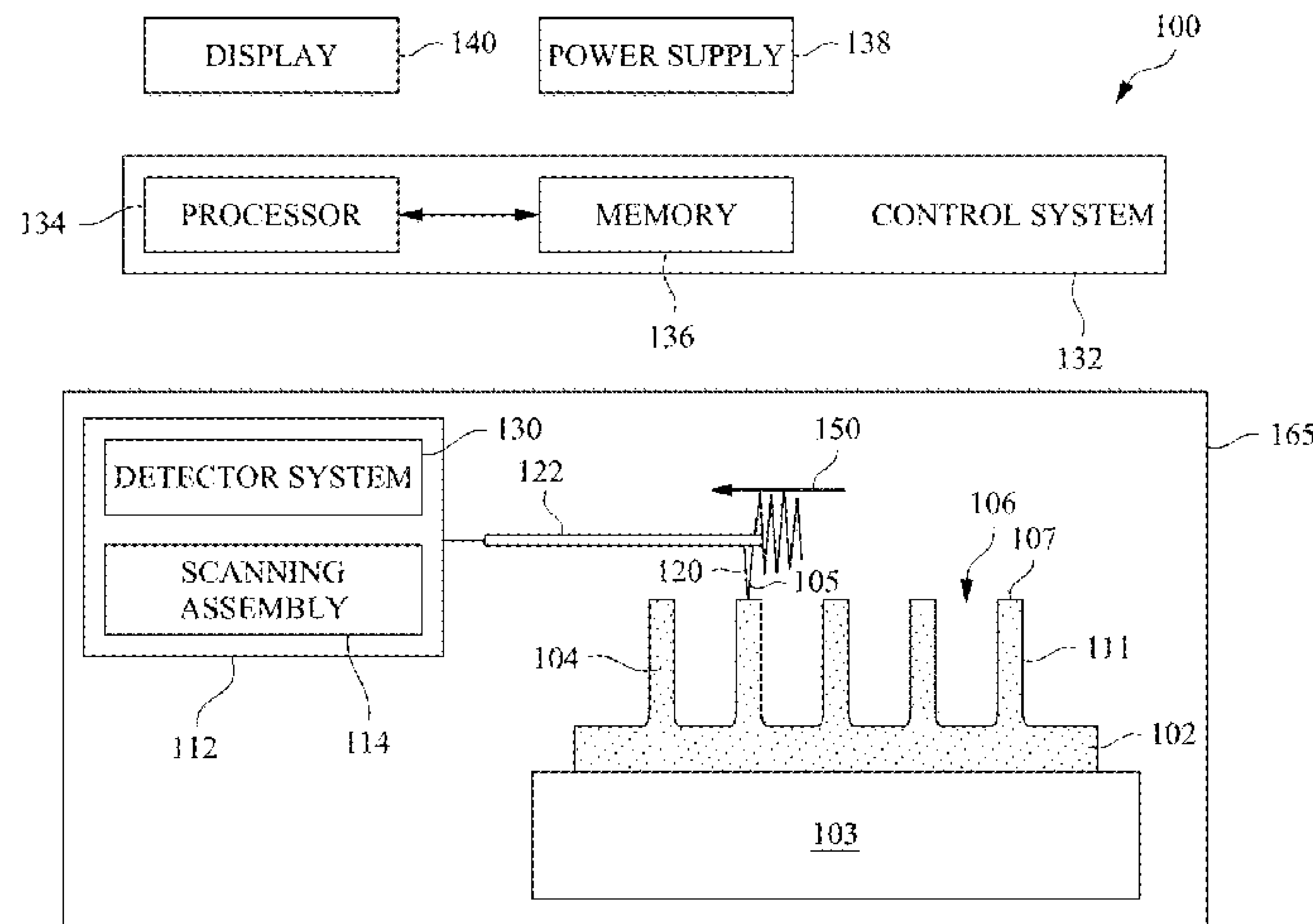

by the processor-based system, calculating line edge roughness of the fins based on the spatial frequency data.

20 Claims, 12 Drawing Sheets

Related U.S. Application Data

continuation of application No. 16/362,283, filed on Mar. 22, 2019, now Pat. No. 10,746,542.

(60) Provisional application No. 62/736,196, filed on Sep. 25, 2018.

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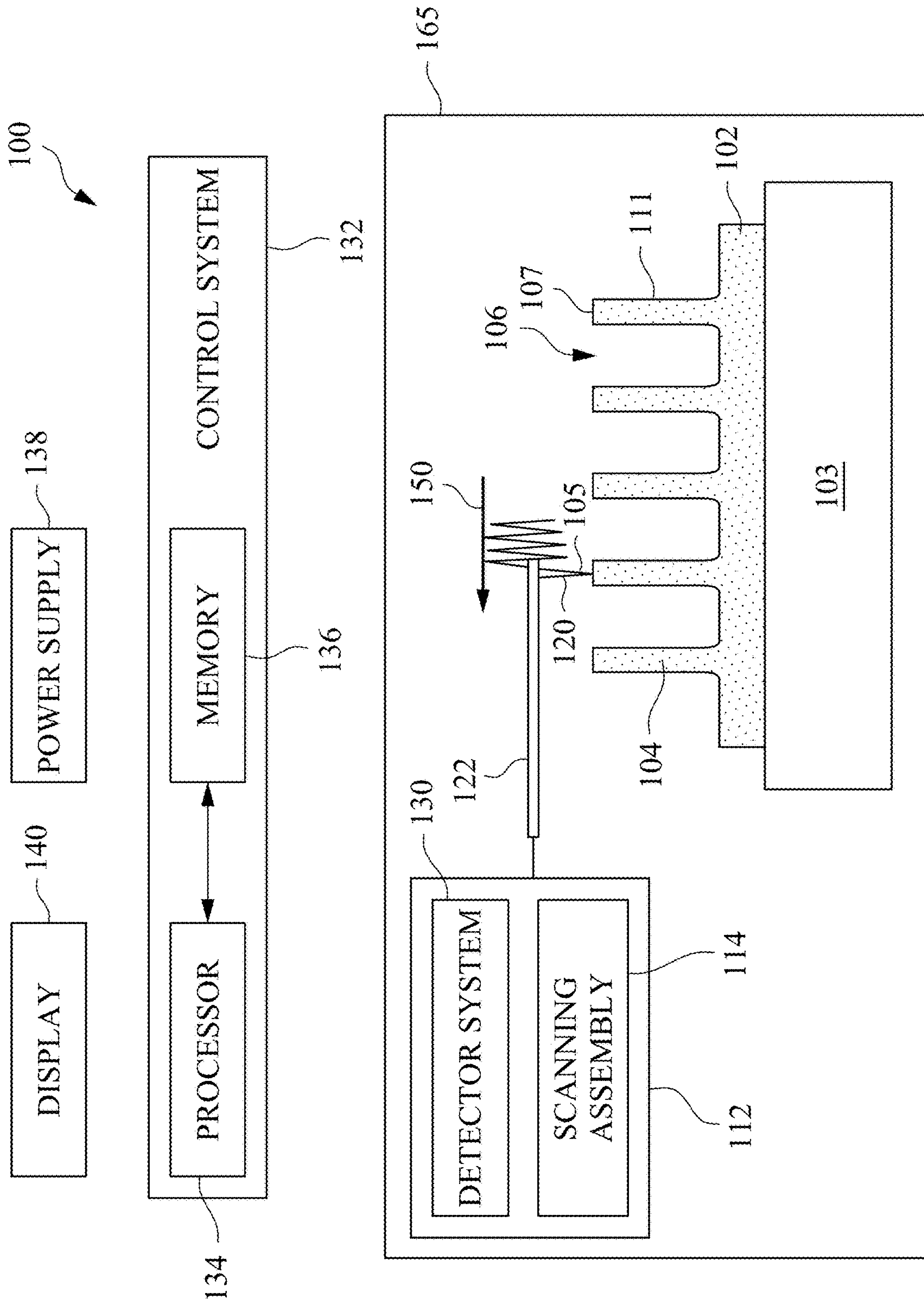

FIG. 1

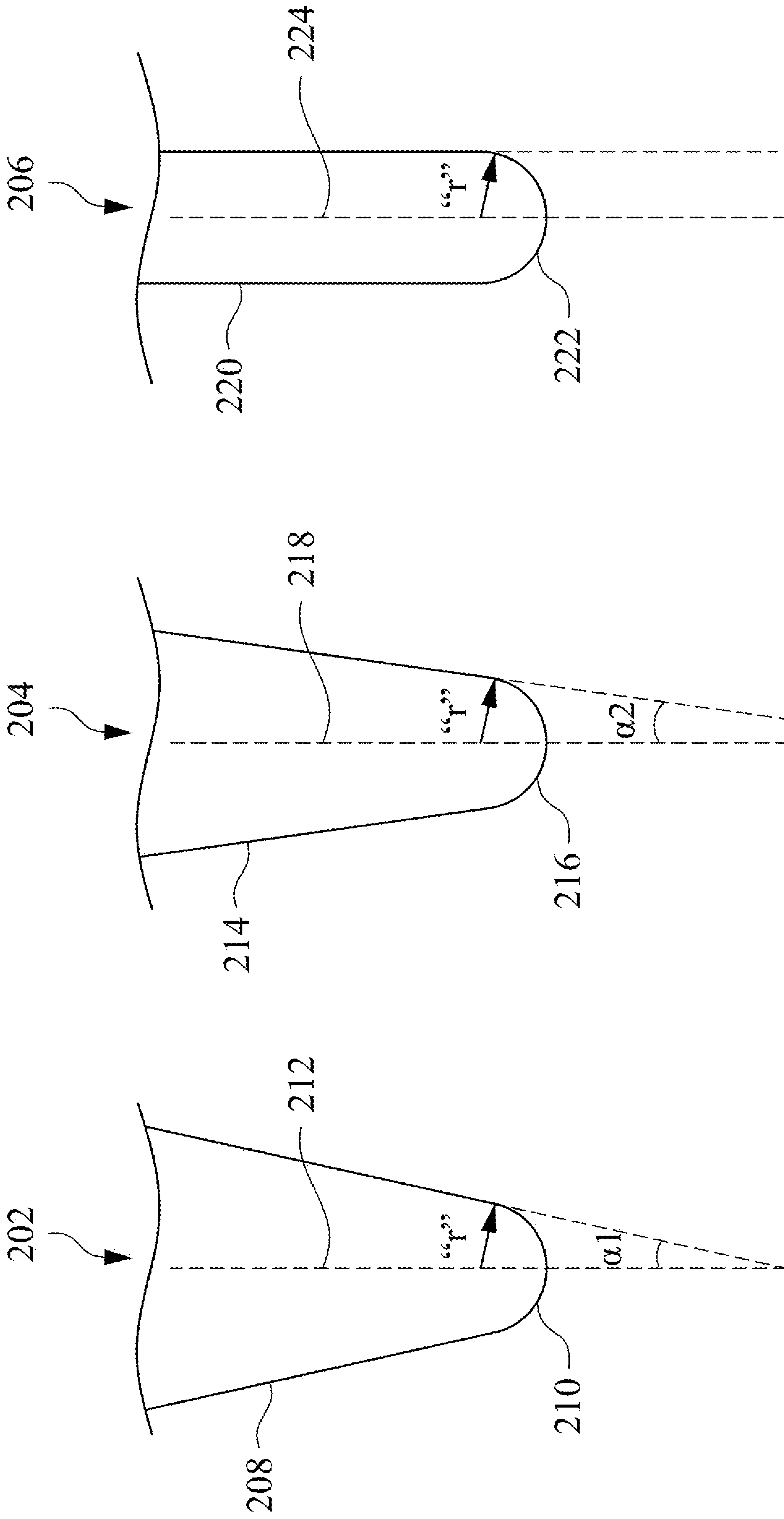

FIG. 2A

FIG. 2B

FIG. 2C

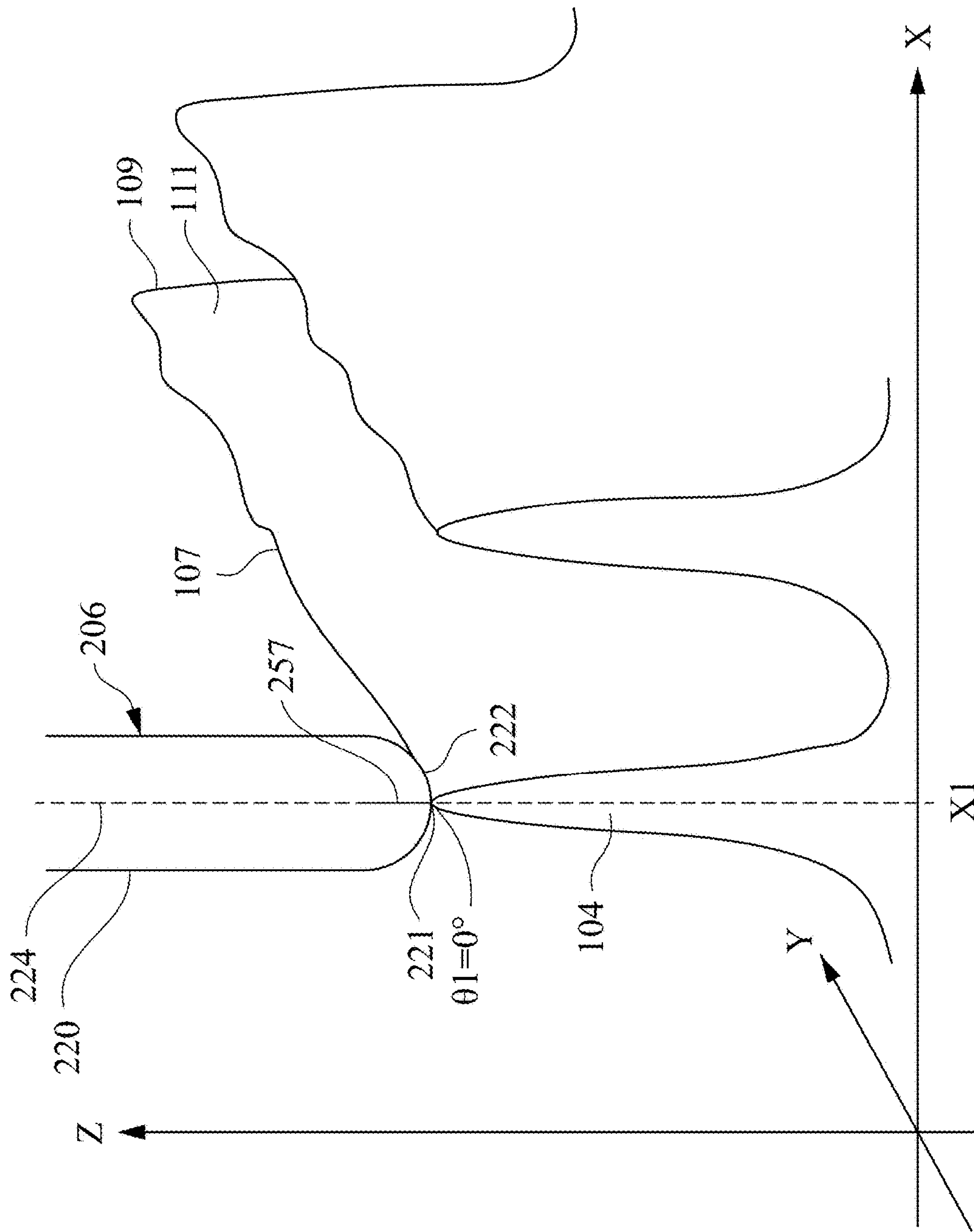

FIG. 3A

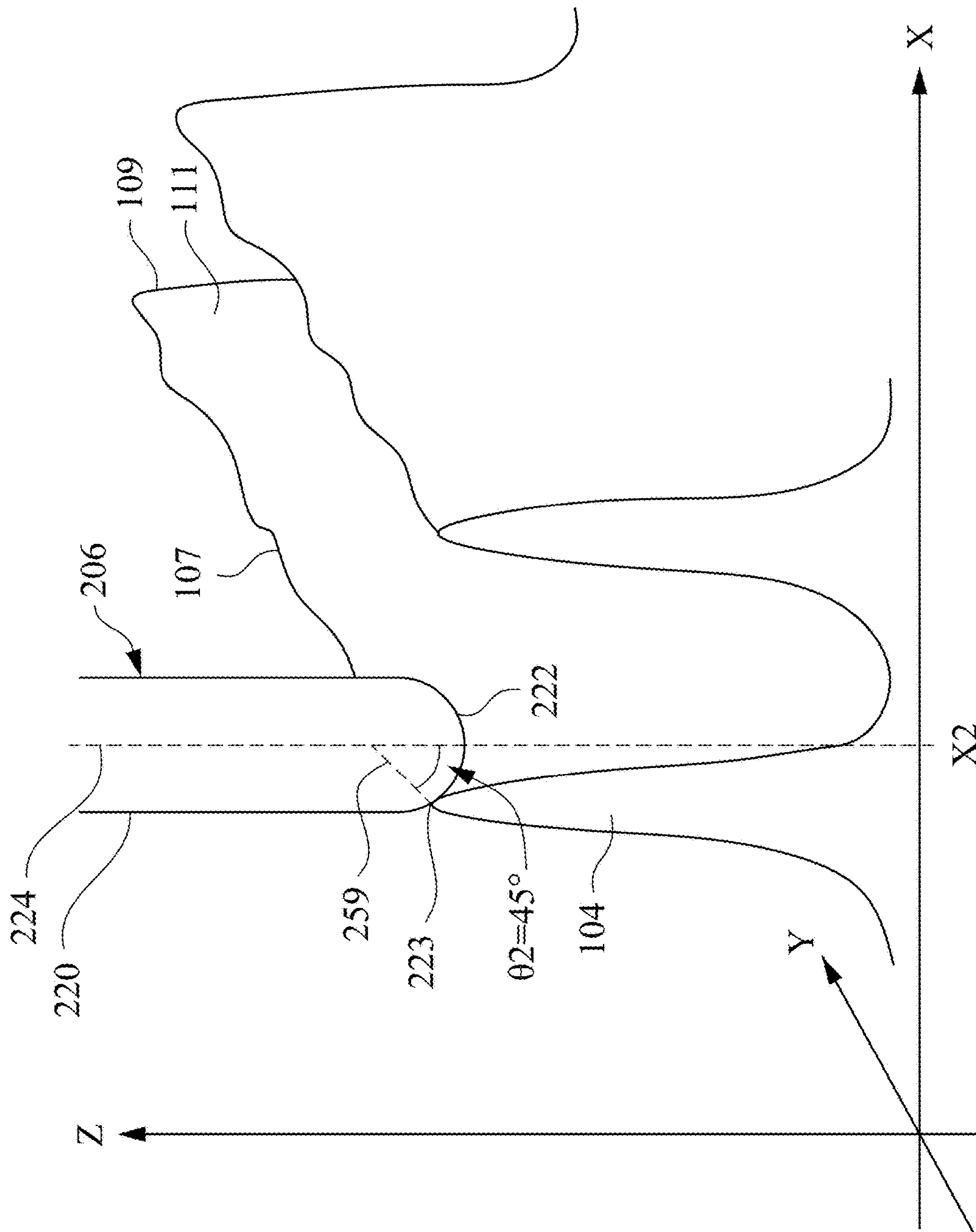

FIG. 3B

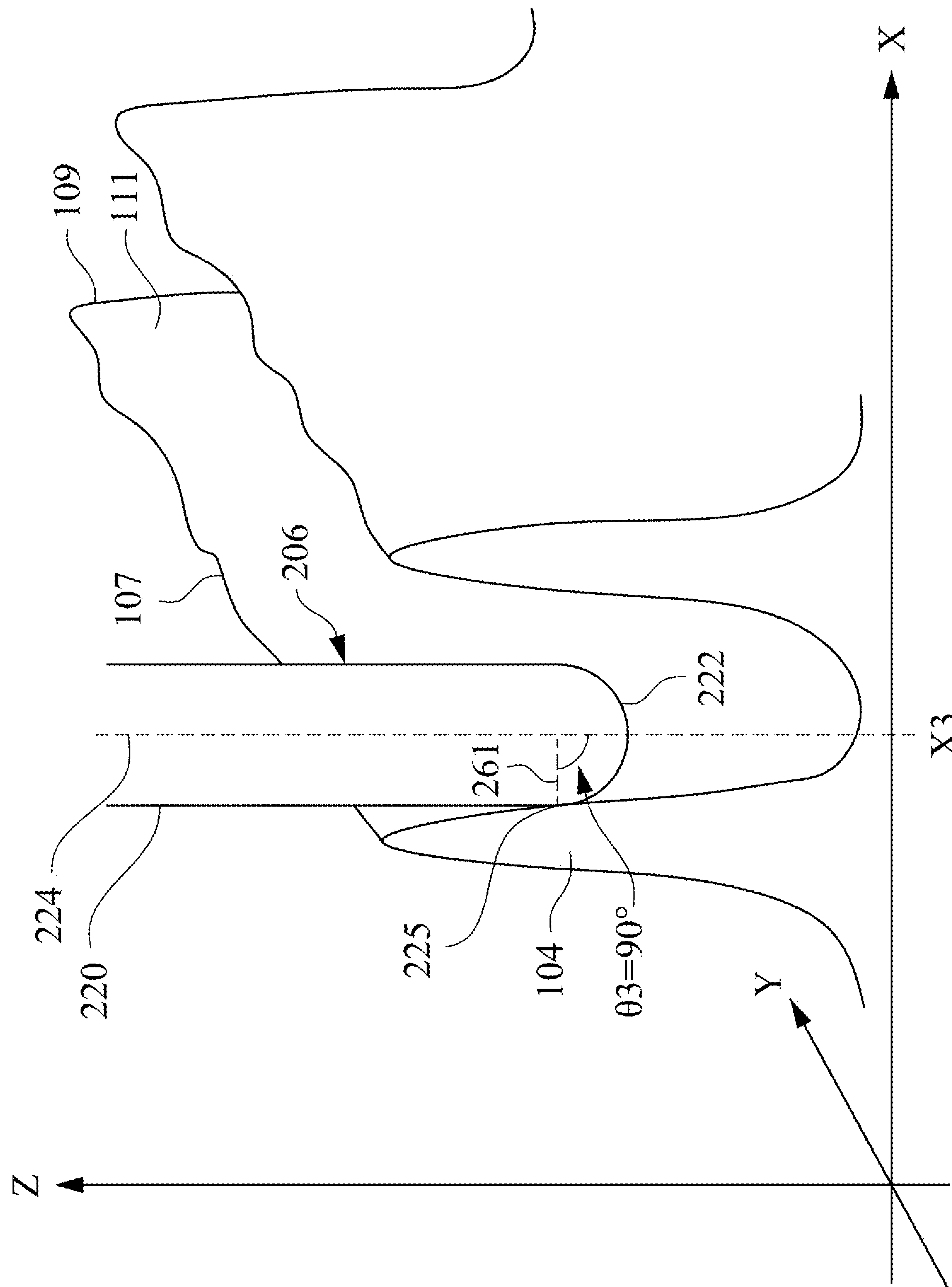

FIG. 3C

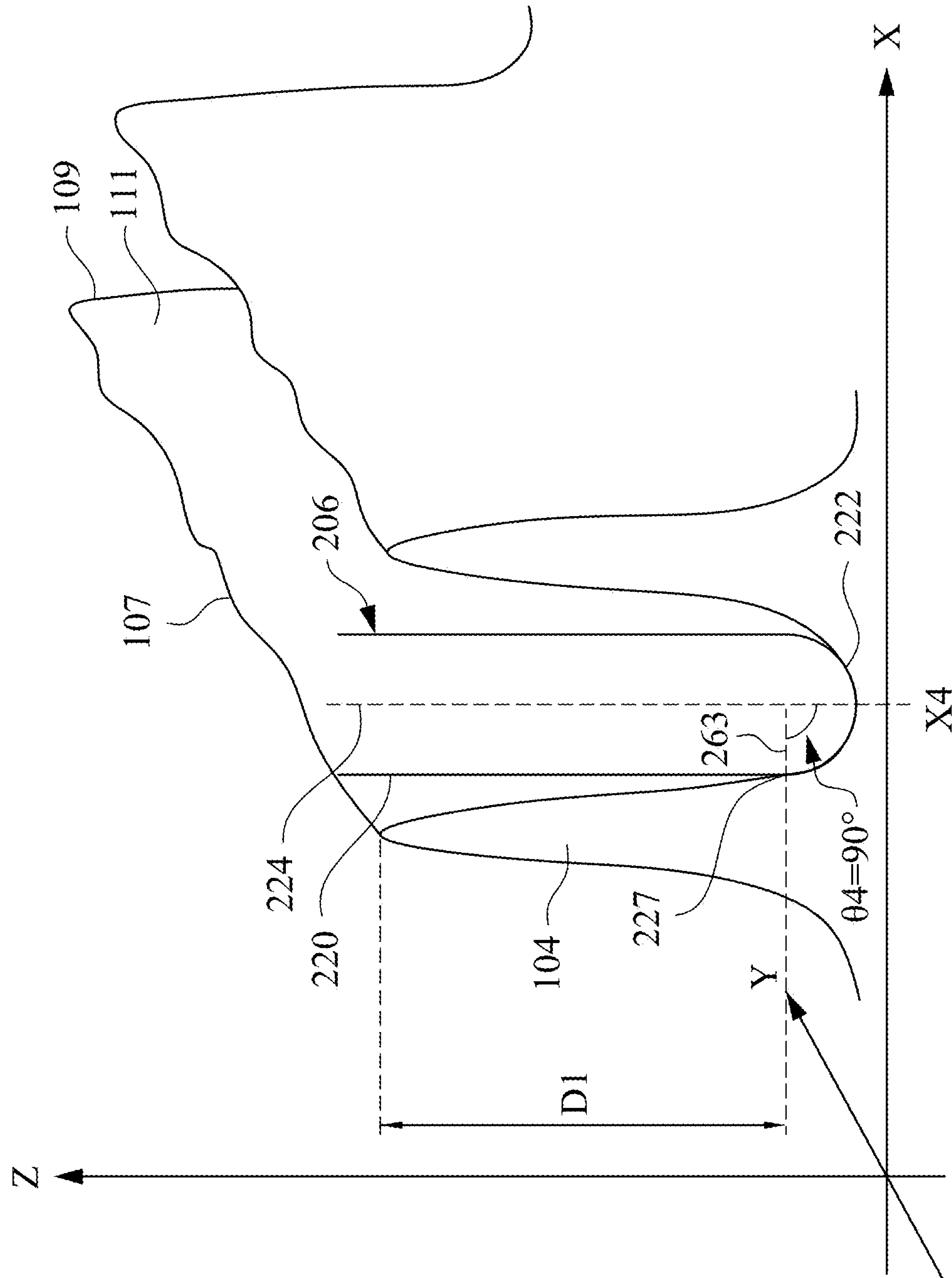

FIG. 3D

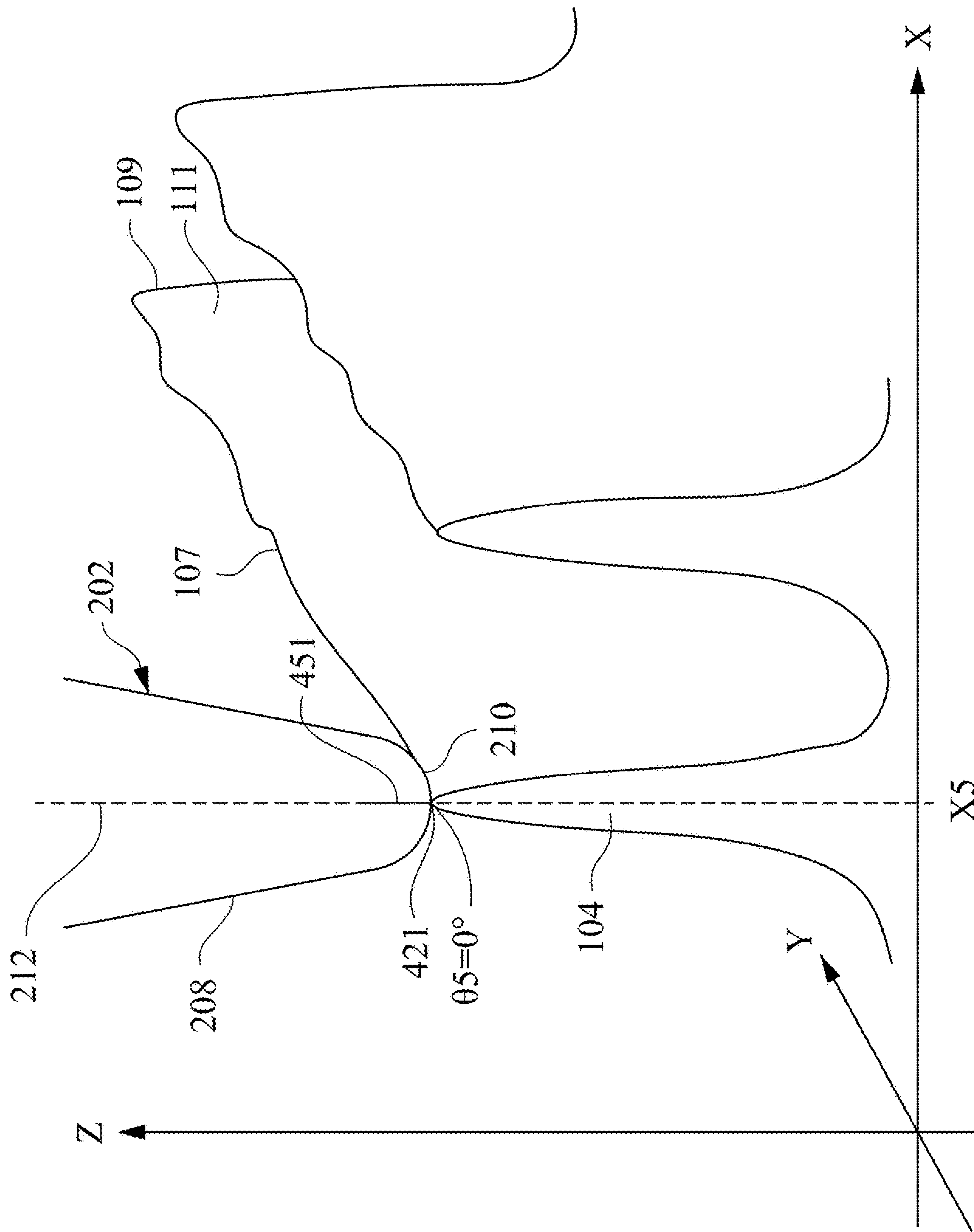

FIG. 4A

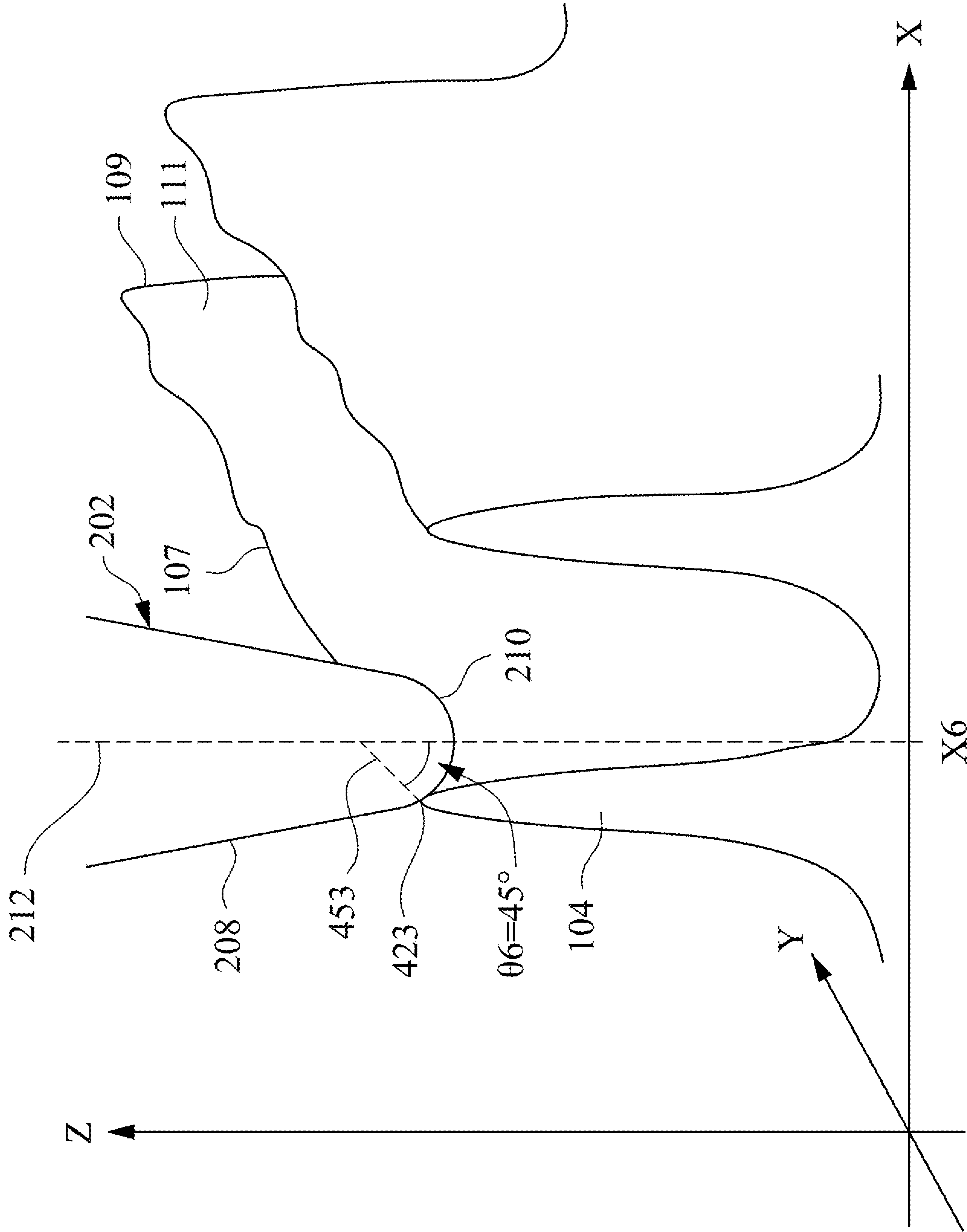

FIG. 4B

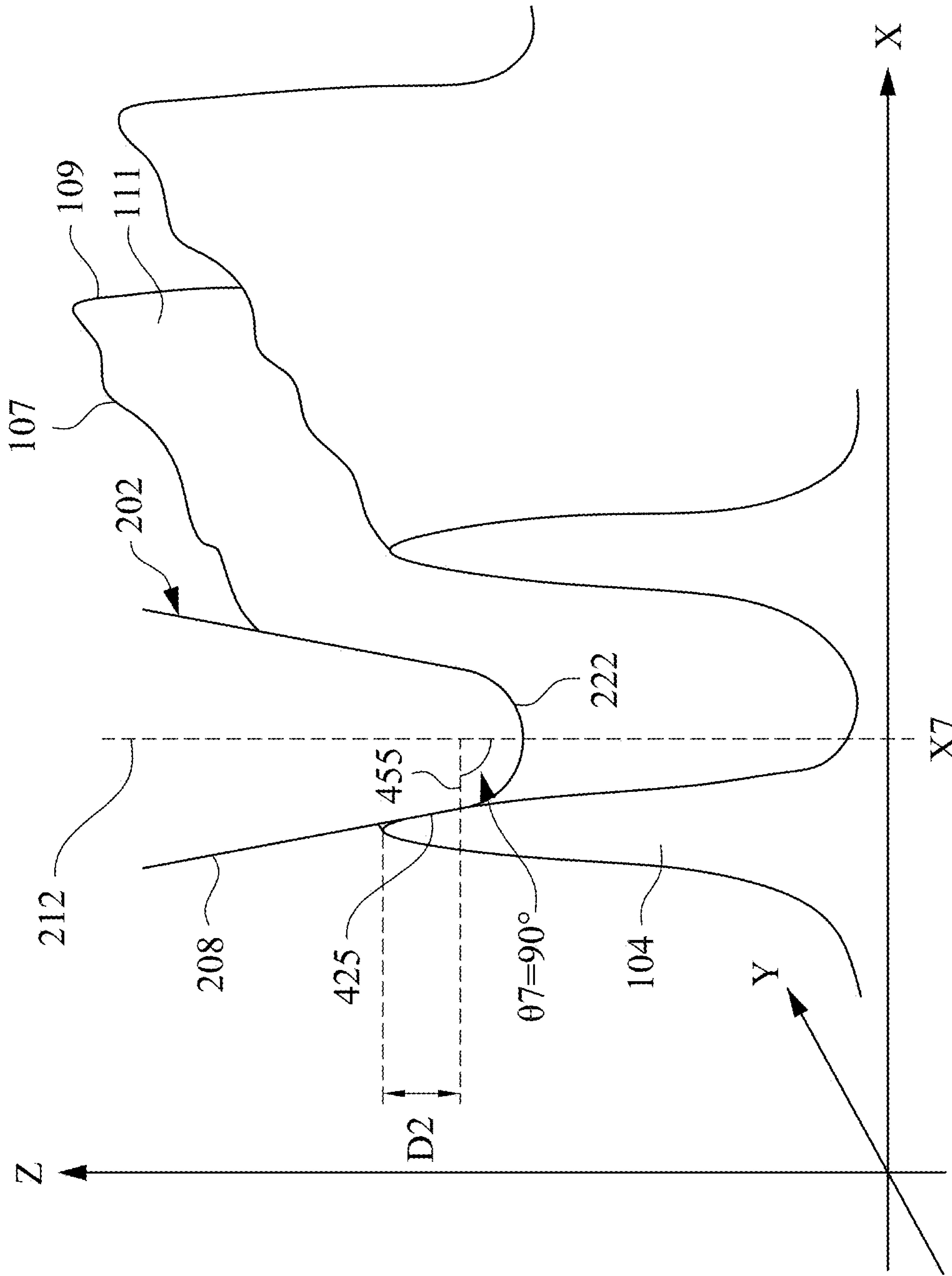

FIG. 4C

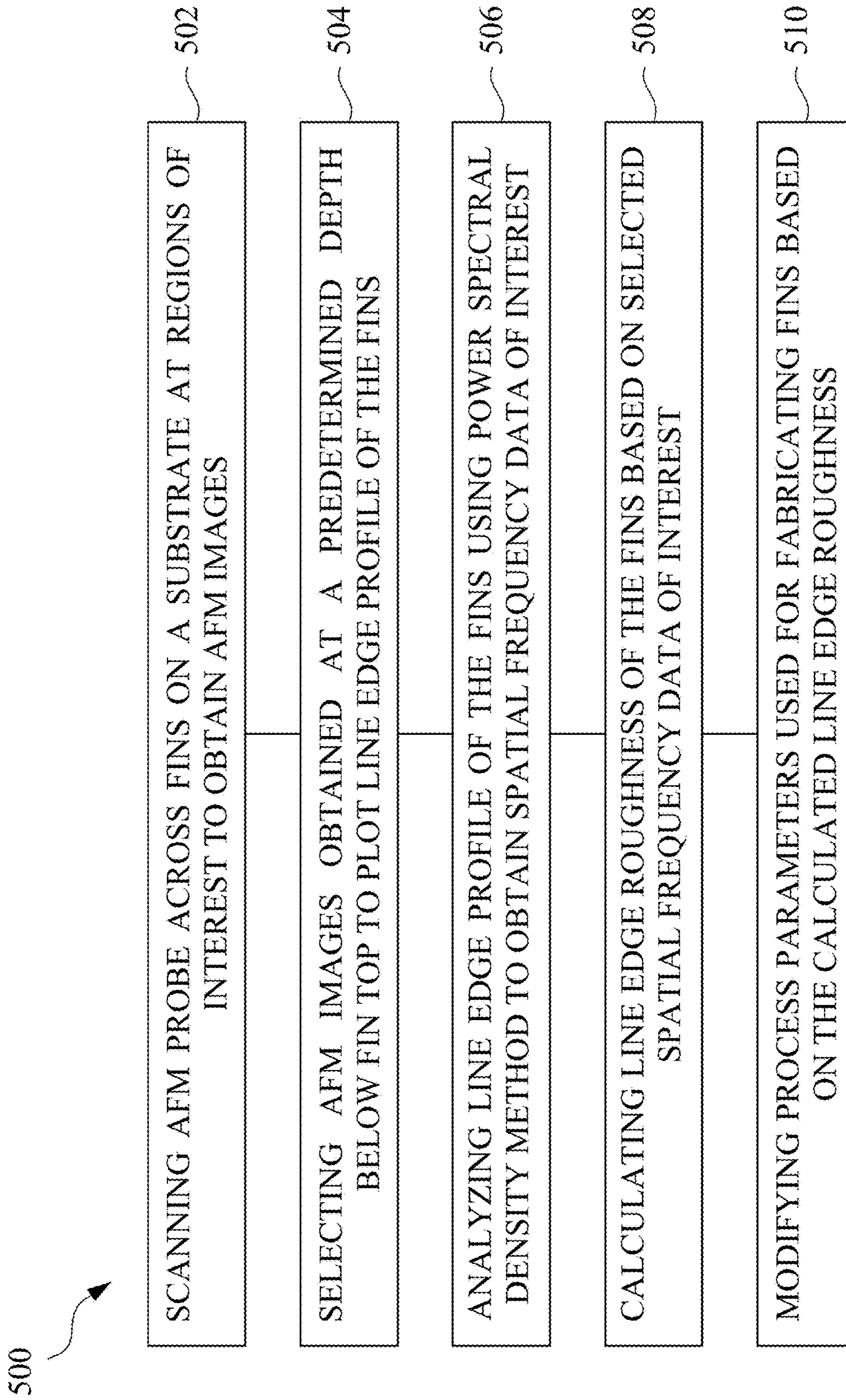

FIG. 5

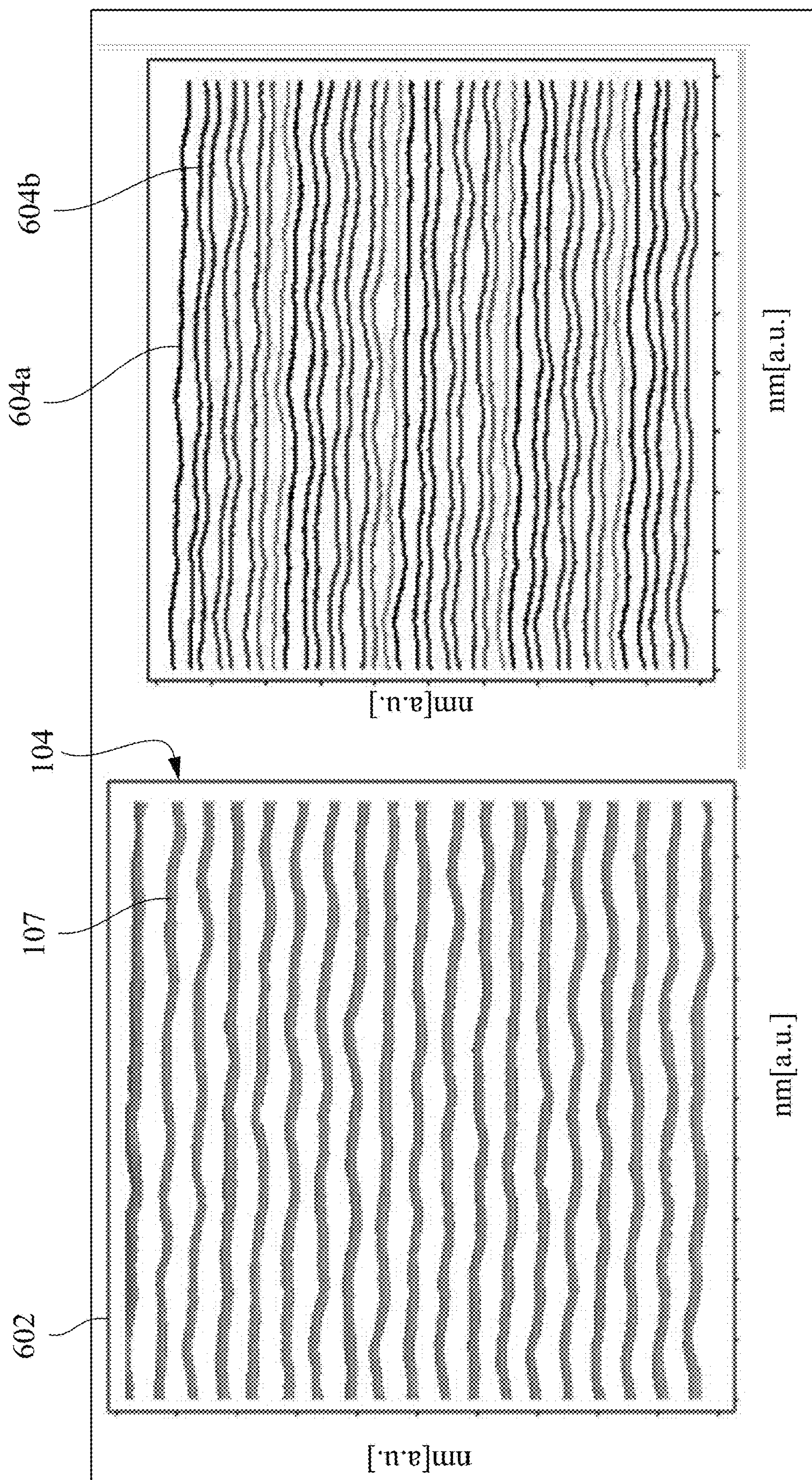

FIG. 6B

FIG. 6A

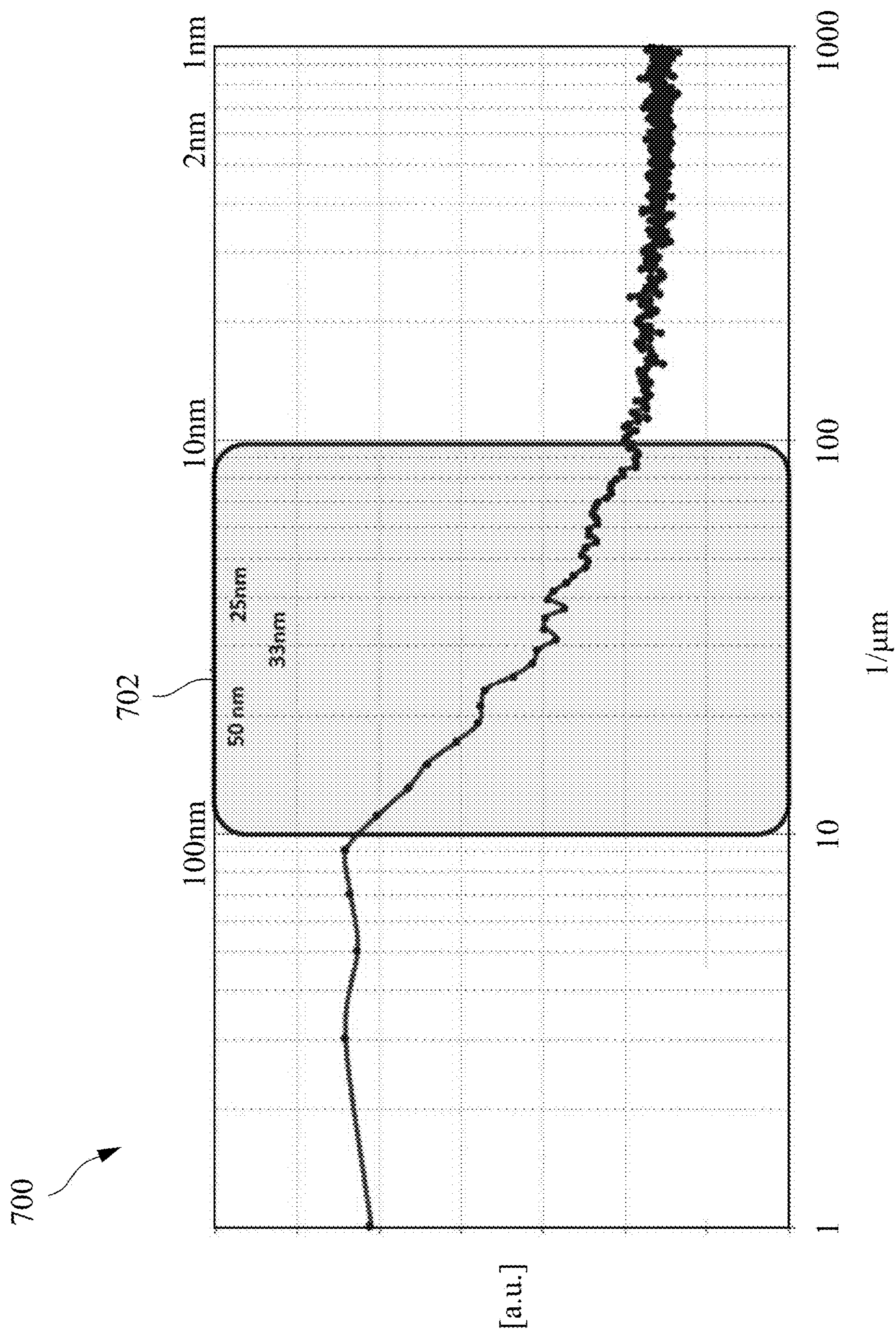

FIG. 7

LINE EDGE ROUGHNESS ANALYSIS USING ATOMIC FORCE MICROSCOPY

BACKGROUND

As the semiconductor industry has progressed into nanometer technology process nodes in pursuit of higher device density, higher performance, and lower costs, challenges from both fabrication and design issues have resulted in the development of three-dimensional designs, such as a Fin Field Effect Transistor (FinFET). FinFET devices typically include semiconductor fins with high aspect ratios and in which channel and source/drain regions are formed. A gate is formed over and along the sides of the fin structure (e.g., wrapping) utilizing the advantage of the increased surface area of the channel to produce faster, more reliable, and better-controlled semiconductor transistor devices.

The line edge roughness of the fin structure can affect the performance of the transistors. To ensure the line edge roughness is maintained within a range desired for downstream processing, a surface measurement technique can be performed to obtain roughness information of the fin structure. However, with the decreasing in scaling, new challenges are presented.

BRIEF DESCRIPTION OF THE DRAWINGS

Aspects of the present disclosure are best understood from the following detailed description when read with the accompanying figures. It is noted that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.

FIG. **1** illustrates a system for measurement and analysis of surface characteristics of a substrate according to some embodiments of the present disclosure.

FIGS. **2**A to **2**C illustrate fragmentary cross-sectional views of different scanning probes according to some embodiments of the present disclosure.

FIGS. **3**A to **3**D illustrate example scanning movement between a cylindrical scanning probe of FIG. **2**C and the fins during a series of interaction periods in accordance with some embodiments of the present disclosure.

FIGS. **4**A to **4**C illustrate example scanning movement between a conical scanning probe of FIG. **2**A and the fins during a series of interaction periods in accordance with some embodiments of the present disclosure.

FIG. **5** is a flowchart illustrating a method of LER analysis for a semiconductor substrate according to some embodiments of the present disclosure.

FIG. **6**A illustrates an example of a top view of line edge profile of the fins at a predetermined depth according to some embodiments of the present disclosure.

FIG. **6**B illustrates edge lines of FIG. **6**A according to some embodiments of the present disclosure.

FIG. **7** is an example power spectral density (PSD) plot for edge lines of FIG. **6**B according to some embodiments of the present disclosure.

DETAILED DESCRIPTION

The following disclosure provides many different embodiments, or examples, for implementing different features of the provided subject matter. Specific examples of components and arrangements are described below to simplify the present disclosure. These are, of course, merely examples and are not intended to be limiting. For example, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed between the first and second features, such that the first and second features may not be in direct contact. In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for the purpose of simplicity and clarity and does not in itself dictate a relationship between the various embodiments and/or configurations discussed.

Further, spatially relative terms, such as "beneath," "below," "lower," "above," "upper" and the like, may be used herein for ease of description to describe one element or feature's relationship to another element(s) or feature(s) as illustrated in the figures. The spatially relative terms are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. The apparatus may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein may likewise be interpreted accordingly.

Various embodiments of this disclosure relate generally to a system and method to determine topographical feature characteristics (e.g., fin line edge roughness) of a semiconductor device, such as a FinFET device. A probe tip oscillating in vertical movement (Z direction) is employed to scan across the three-dimensional structure (e.g., fins, gates, or metal lines, etc.) of the semiconductor device in an X and/or Y direction to obtain feature characteristics (e.g., line edge profile) of the fins at the target regions of the substrate. The line edge profile is then analyzed using a power spectral density (PSD) method to extract line edge roughness (LER) of the fins at a spatial frequency domain of interest. The vertical oscillation allows the probe tip to reach different depths from the fin top and be in close proximity to the bottom between the adjacent fins. Therefore, sub-nanometer resolution images of the fin top and region near the fin top can be obtained. The information of the extracted line edge roughness of the fins can be used to refine or correct fin fabrication process so as to form fins with reduced LER.

FIG. **1** illustrates a system **100** for measurement and analysis of surface characteristics of a substrate **102** according to some embodiments of the present disclosure. The substrate **102** as shown may be a portion of an intermediate structure of a semiconductor device, such as a FinFET device. The substrate which may be a bulk semiconductor substrate, a semiconductor-on-insulator (SOI) substrate, or the like, which may be doped (e.g., with a p-type or an n-type dopant) or undoped. The substrate **102** may include an elemental semiconductor including silicon (Si) or germanium (Ge); a compound semiconductor; an alloy semiconductor; or a combination thereof. The substrate **102** has a plurality of fins **104**. Each fin **104** can provide an active area where one or more integrated devices are formed or to be formed. The fins **104** may be fabricated using suitable processes performed on the substrate **102**, including masking, photolithography, and/or etch processes, to form trenches **106** into the substrate **102**, thereby forming the fins **104** extended upwardly from the substrate **102**. The trenches **106** may have an aspect ratio of about 3:1 to about 30:1, for example about 5:1 to about 20:1. The term "aspect ratio" in this disclosure refers to the ratio of the height dimension to the width dimension of a particular feature, for example, trench height/trench width. The trench height substantially equals to the height of the fins **104** protruding above the

substrate **102** while the trench width substantially equals to the width or distance of the region between two neighboring fins **104**.

The fins **104** may be patterned by any suitable method. For example, the fins **104** may be patterned using one or more photolithography processes, including double-patterning or multi-patterning processes. Generally, double-patterning or multi-patterning processes combine photolithography and self-aligned processes, allowing patterns to be created that have, for example, pitches smaller than what is otherwise obtainable using a single, direct photolithography process. For example, in some embodiments, a sacrificial layer is formed over a substrate and patterned using a photolithography process. Spacers are formed alongside the patterned sacrificial layer using a self-aligned process. The sacrificial layer is then removed, and the remaining spacers may then be used to pattern the fins **104** and form the trenches **106**.

The system **100** generally includes a scanning probe microscope (SPM) **112** having a scanning assembly **114**. The SPM **112** may be an atomic force microscope (AFM) or a scanning tunneling microscopy (STM). The SPM **112** is used to measure surface properties of the substrate **102** disposed on a stage **103**. The scanning assembly **114** includes, or is operatively connected to, a scanning probe **120**, for measuring the surface topography of the fins **104**. While one scanning probe **120** is shown, in some embodiments, the scanning assembly **114** may include two or more scanning probes operating simultaneously to increase scanning throughput.

The scanning probe **120** may be made from a metal, carbon nanotube or semiconductor material, such as silicon. The scanning probe **120** can be placed on or brought immediately adjacent to the top surface **107** of the fins **104**. While the scanning probe **120** is illustrated as having a substantially conical probe tip **105**, other shapes of probe tips may be utilized. Example shape of the probe tips are further discussed below with respect to FIGS. **2**A to **2**C. The scanning probe **120** is coupled to an oscillating actuator (not shown) through a cantilever **122**, which may also be made from a semiconductor material such as silicon. The actuator may move the scanning probe **120** in any direction with respect to the substrate **102** being analyzed. Additionally or alternatively, the substrate **102** may move in any direction relative to the scanning probe **120**. In either case, an image of the substrate **102** is acquired by scanning the scanning probe **120** over the fins **104** at target regions of the substrate **102**. The relative movement between the scanning probe **120** and the substrate **102** will be discussed in more detail below in FIGS. **3**A to **3**D and **4**A to **4**C.

The SPM **112** also includes a detector system **130** for detecting movement of the scanning probe **120** relative to the substrate **102**, which movement corresponds to surface characteristics of the substrate **102**. The surface characteristics may include line edge roughness (LER) of the fins **104**, fin sidewall profile, and/or fin sidewall roughness. The scanning probe **120** is controlled to move the probe tip **105** up and down commensurate with the surface characteristics of the fins **104** while scanning in the X and/or Y direction. The scanning probe **120** may operate in a contact mode, in which the probe tip **105** is in contact with the surface of the fins **104**, or a non-contact mode, in which the probe tip **105** is maintained at a spacing above the surface of the fins **104**. The cantilever **122** deflects in response to electrostatic, magnetic, van der Waals or other forces between the probe tip **105** and the surface of the fins **104**. In these cases, the deflection of the cantilever **122** from which the probe tip **105** projects is measured. In some embodiments, the scanning probe **120** may operate in a tapping mode where the scanning probe **120** is oscillated vertically at or near a resonant frequency of the cantilever **122** in the vicinity of the surface of the fins **104** so that the probe tip **105** makes intermittent contacts (tapping) with the surface once in every oscillation period. In some embodiments, the cantilever **122** may be moved at scanning frequencies in a range of about 2 Hz to about 20 Hz, for example about 5 Hz to about 10 Hz. The substrate **102** may be transferred to an environmentally controlled chamber **165** where the scanning operations are performed. In one embodiment, the chamber **165** is maintained at a dry condition in which the moisture is under 0.5 ppm and oxygen is under 1 ppm. The dry condition can help prevent moisture from building up on the surface of the substrate **102**, which would otherwise degrade the image resolution and lifetime of the probe tip **105**. In some embodiments, the scanning operations may be performed under vacuum or atmospheric condition.

The detector system **130** can detect the movement of the scanning probe **120** to provide measurement data that is passed to a control system **132**. The detector system **130** may employ any suitable sensing mechanism to detect movement of the scanning probe **120**. For example, an optical detection scheme may be used, in which a beam of light (e.g., a laser beam) is reflected or diffracted by the probe tip **105** or the cantilever **122** an amount proportional to the movement of the scanning probe **120**. The beam may be detected at a photodetector that provides an output signal indicative of the detected movement of the scanning probe **120**. The output signal therefore reflects the topography of the surface of the fins **104**. The output signals are then provided to the control system **132**. The control system **132** may include a processor **134**, which may be programmed to control operation of the various components within the system **100** in order to perform various functions described in this disclosure. While one processor **134** is shown, it is contemplated that a plurality of processors and/or processing systems may be included as part of and/or external to the system **132** for performing signal analysis.

The system **100** also includes a memory **136** operatively connected to the processor **134** for storing computer-executable instructions, which may be executed by the processor **134** to perform operations and/or signal analysis discussed in this disclosure, such as the method to be discussed below with respect to FIG. **5**. The memory **136** may be a non-transitory computer readable medium including, for example, read only memory (ROM) or random access memory (RAM). The RAM can be the main memory where the operating system and application programs are located. The memory **136** may also serve as a storage medium for temporarily storing information such as the measurement date (e.g., amplitude, probe tip position relative to the substrate surface, etc.), substrate position, line edge profile, statistical data, programs for determining surface characteristics of the substrate from measurement data, and/or other data which may be employed to perform embodiments of the present disclosure. If needed, the memory **136** may also include a hard drive or other suitable nonvolatile storage medium.

A power supply **138** is coupled to the system **100** to provide power to the system **100**. The system **100** may include a display **140** for displaying an image constructed based on the measurement data. The control system **132** may include any other components for communicating, e.g., measurement data to other systems via a network, for

inputting and/or outputing data such as via a keyboard, mouse, printer, etc., or for any other functionality of a computing system.

The control system **132**, for example, the processor **134**, is operable to control the scanning of the scanning probe **120** over the surface of the fins **104**. The scanning probe **120** may scan across the substrate **102** in any direction or desired pattern. For example, the scanning probe **120** may move in a direction **150** perpendicular to the longitudinal direction of the fins **104**. Alternatively, the scanning probe **120** may move in a direction **150** along the longitudinal direction of the fins **104**. The processor **134** may further control scanning intervals of the scanning probe **120** by adjusting the position of the probe tip **105** in any direction between each scanning interval. For example, a position device (not shown) may be used to provide relative movement between the scanning probe **120** and the substrate **102** for selectively scanning target regions of the substrate **102**.

The processor **134** can be programmed to analyze the measurement data obtained from the detector system **130** according to various embodiments of the present disclosure. The scanning probe **120** moves across the surface of the substrate **102** and produces measurement data that is generated by the detector system **130** and from which the processor **134** may determine selected surface characteristics of the fins **104** and/or construct a topographic image (e.g., a line edge profile, a graphical outline, etc.) of the fins **104** with resolution according to the dimension of the probe tip **105**. A topographic image may be directed to the display **140** by the control system **132**.

FIGS. **2**A to **2**C illustrate a fragmentary cross-sectional view of three different scanning probes **202**, **204**, **206** that according to some embodiments of the present disclosure. The scanning probes **202**, **204**, **206** may be and/or replace the scanning probe **120** of FIG. **1**. The scanning probes **202**, **204**, **206** are sized to allow their probe tips to penetrate into the narrow space between dense fins **104**. The scanning probes **202**, **204**, **206** use spherical-shaped probe tips and vary in cross-sectional profiles to provide different measurement depth below the fin top, as will be discussed in more detail below in FIGS. **3**A to **3**D and **4**A to **4**C. The scanning probe **202** shown in FIG. **2**A has a conical sidewall **208** and a probe tip **210**. The conical sidewall **208** has a profile that expands away from the probe tip **210**. The conical sidewall **208** extends in a direction that is at an angle "α1" with respect to the longitudinal axis **212** of the scanning probe **202**. In an embodiment, the angle "α1" is in a range from about 1° to about 25°, such as about 8° to about 20°, for example about 10° to about 16°, for example about 13°. The scanning probe **204** shown in FIG. **2**B is similar to the scanning probe **202** shown in FIG. **2**A except that a less-inclined sidewall probe is adapted. The scanning probe **204** also has a conical sidewall **214** and a probe tip **216**. The conical sidewall **214** extends in a direction that is at an angle "α2" with respect to the longitudinal axis **218** of the scanning probe **204**. In an embodiment, the angle "α2" is in a range from about 1° to about 25°, such as about 2° to about 10°, for example about 2° to about 4°. The scanning probe **206** shown in FIG. **2**C is a cylindrical probe having straight parallel sidewall **220** and a probe tip **222**. The scanning probe **206** exhibits a cross sectional profile that is relatively constant along at least a portion of its length. Therefore, the sidewall **220** is parallel to the longitudinal axis **224** of the scanning probe **206**.

Each of the probe tips **210**, **216**, **222** of the scanning probes **202**, **204**, **206** has a spherical-shaped probe tip. A spherical-shaped probe tip has a consistent tip radius that can ensure consistent image quality of atomic force microscopy. This is because the scanning resolution provided by the spherical-shaped probe tip is generally constant regardless of which point of the probe tip contacts the surface of the substrate. The diameter of the scanning probes **202**, **204**, **206** is chosen to be smaller than fin-to-fin spacing between neighboring pairs of the fins so that the scanning probes, at least the probe tips **210**, **216**, **222**, can penetrate the narrow space between dense fins. The fin-to-fin spacing may be in a range from about 10 to about 30 nm. In an embodiment, the probe tips **210**, **216**, **222** may have a probe tip radius "r" in a range from about 1 nm to about 15 nm, for example about 2 nm to about 5 nm. The consistent tip radius of less than 10 nm can provide good resolution and reproducibility. It is contemplated that the fin-to-fin spacing and/or the probe tip radius may vary depending on the application.

FIGS. **3**A to **3**D illustrate example scanning movement between the scanning probe **206** of FIG. **2**C and the fins during a series of interaction periods in accordance with some embodiments of the present disclosure. A piezoelectric tube (not shown) may move the scanning probe **206** in a direction along an X-axis to scan across a surface of a fin, such as the fins **104** of the substrate **102** shown in FIG. **1**. In an embodiment shown in FIGS. **3**A to **3**D, the scanning probe **206** may incrementally move along the X-axis at a predetermined travel distance of about 0.05 nm to about 5 nm, for example about 0.5 nm to about 1 nm. The travel distance in this disclosure refers to a distance between two tip-sample contacts during the scanning, which may vary depending upon the application and/or the pitch distance between two immediately adjacent fins.

FIG. **3**A shows that the scanning probe **206** is driven into vertical oscillation in a tapping-mode and engaged with a top surface **107** of the fin **104**. The scanning probe **206** is oscillated at a frequency of about 45 kHz to about 620 kHz, for example about 400 kHz. The probe tip **222** contacts the top surface **107** of the fin **104** at a first scanning location X1. The probe tip **222** contacts the top surface **107** at the contact point **221**. The longitudinal axis **224** of the scanning probe **206** forms an angle "θ1" with respect to a line **257** normal to the tangential plane of the probe **206** at the contact point **221**. In this example, the angle "θ1" is about 0° since the scanning probe **206** contacts the top surface **107** of the fin **104** through the bottom of the probe tip **222**. FIG. **3**B shows that the scanning probe **206** moves to a second scanning location X2 and engages with an edge **109** of the fin **104**. The probe tip **222** contacts the edge **109** of the fin **104** at the contact point **223**. The longitudinal axis **224** of the scanning probe **206** forms an angle "θ2" of about 45° with respect to a line **259** normal to the tangential plane of the probe **206** at the contact point **223**. FIG. **3**C shows that the scanning probe **206** moves to a third scanning location X3 and engages with an upper portion of the sidewall **111** of the fin **104**. The probe tip **222** contacts the upper portion of the sidewall **111** at the contact point **225**. The longitudinal axis **224** of the scanning probe **206** forms an angle "θ3" of about 90° with respect to a line **261** normal to the tangential plane of the probe **206** at the contact point **225**. FIG. **3**D shows that the scanning probe **206** moves to a fourth scanning location X4 and engages with a lower portion of the sidewall **111** of the fin **104**. The probe tip **222** contacts the lower portion of the sidewall **111** at the contact point **227**. The longitudinal axis **224** of the scanning probe **206** forms an angle "θ4" of about 90° with respect to a line **263** normal to the tangential plane of the probe **206** at the contact point **227**.

As can be seen in FIG. **3**D, the cylindrical scanning probe **206** allows the probe tip **222** to penetrate the narrow space

between dense fins **104** and reach the bottom. Therefore, the scanning probe **206** can fully access (and obtain images of) the sidewalls **111** of the fins **104** at different depths. Particularly, the resolution of the images obtained by the scanning probe **206** can be consistent from fin top to bottom regardless of which point of the probe tip **222** contacts the fin **104** because the spherical-shaped probe tip **222** has a consistent tip radius. The cylindrical scanning probe **206** and the spherical-shaped probe tip **222** thus can provide an effective measurement depth "D1" substantially corresponding to the height of the fins **104**. Therefore, the surface characteristics at any depth of the fins **104** can be acquired to provide good line edge roughness (LER) analysis.

In some embodiments, the effective measurement depth "D1" is in a range from greater than about 0 nm to about 80 nm, such as about 5 nm to about 50 nm, for example about 10 nm. The term "effective measurement depth" refers to a distance from a fin top to a depth of the sidewall where the probe tip makes physical contact during the scanning. Therefore, the effective measurement depth can be decreased or increased depending on what type of probe is used. A sharp probe can result in an increased effective measurement depth.

FIGS. **4**A to **4**C illustrate example scanning movement between the scanning probe **202** of FIG. **2** and the fins **104** during a series of interaction periods in accordance with some embodiments of the present disclosure. The scanning probe **202** is shown to move incrementally along the X-axis at a predetermined distance of about 0.05 nm to about 5 nm, for example about 0.5 nm to about 1 nm. Likewise, the scanning probe **202** is driven into vertical oscillation in a tapping-mode and engages with the top surface **107** of the fin **104**, which then scans the surface at a scanning speed about 2 Hz to about 20 Hz. Likewise, the scanning probe **202** is oscillated at a frequency of about 45 kHz to about 620 kHz, for example about 400 kHz.

FIG. **4**A shows that the probe tip **210** contacts the top surface **107** of the fin **104** at a fifth scanning location X5. The probe tip **210** contacts the fin **104** at the contact point **421**. The longitudinal axis **212** of the scanning probe **202** forms an angle "θ5" with respect to a line **451** normal to the tangential plane of the probe **202** at the contact point **421**. In this example, the angle "θ5" is about 0° since the scanning probe **202** contacts the top surface **107** of the fin **104** through the bottom of the probe tip **210**. FIG. **4**B shows that the scanning probe **202** moves to a sixth scanning location X6 and engages with an edge **109** of the fin **104**. The probe tip **210** contacts the edge **109** of the fin **104** at the contact point **423**. The longitudinal axis **212** of the scanning probe **202** forms an angle "θ6" of about 45° with respect to a line **453** normal to the tangential plane of the probe **202** at the contact point **423**. FIG. **4**C shows that the scanning probe **202** moves to a seventh scanning location X7 and engages with an upper portion of the sidewall **111** of the fin **104**. The probe tip **210** contacts the upper portion of the sidewall **111** at the contact point **425**. The longitudinal axis **212** of the scanning probe **202** forms an angle "θ7" of about 90° with respect to a line **455** normal to the tangential plane of the probe **202** at the contact point **425**.

The use of the spherical-shaped probe tip **210** also allows the scanning probe **202** to provide images of the sidewalls **111** at different depths below the fin top with high resolution. However, due to the conical profile of the scanning probe **202**, the scanning probe **202** may have an effective measurement depth "D2" shorter than the measurement depth "D1" provided by the cylindrical scanning probe **206**. In some embodiments, the effective measurement depth "D2" is in a range from greater than about 0 nm to about 80 nm, such as from about 5 nm to 50 nm, for example about 10 nm. Therefore, the effective measurement depth can be increased if a sharp probe is used. While not discussed herein, it is contemplated that scanning probes with a less-inclined sidewall, such as the scanning probe **204** shown in FIG. **2**B, may be used to provide a greater measurement depth in a range from about 35 nm to about 100 nm.

The scanning probes **202**, **204**, **206** are sized to penetrate into the narrow space between the fins and obtain sub-nanometer resolution AFM images by oscillating the probe tips in vertical movement. The vertical oscillation allows the probe tip to reach different depths from the fin top and be in close proximity to the bottom. Therefore, sub-nanometer resolution images of the fin top and region near the fin top (such as the region within the effective measurement depth of the scanning probes used for obtaining AFM images) can be obtained.

Embodiments of the present disclosure can provide high resolution AFM images of the fin top and/or region near the fin top, such as the region within the effective measurement depth of the scanning probes used for obtaining AFM images. High resolution AFM images obtained by the scanning probes **202**, **204**, **206** can be selected and processed to provide line edge profile of the fins at a predetermined depth below the fin top for precise LER analysis. FIG. **5** is a flowchart **500** illustrating a method of LER analysis for a semiconductor substrate according to some embodiments of the present disclosure. Although various operations are illustrated in the drawings and described herein, no limitation regarding the order of such steps or the presence or absence of intervening steps is implied. Operations depicted or described as sequential are, unless explicitly specified, merely done so for purposes of explanation without precluding the possibility that the respective steps are actually performed in concurrent or overlapping manner, at least partially, if not entirely.

The flowchart **500** begins at operation **502** by using an atomic force microscope (AFM) to scan across a substrate at regions of interest. The AFM can be the SPM **112** as discussed above in FIG. **1**. The SPM **112** may use the scanning probe **120**, or the scanning probes **202**, **204**, **206** as discussed above with respect to FIGS. **1** and **2**, for performing the scanning. The regions of interest may include, for example, center, edge, any location between the center and edge of the substrate, or any combination thereof. In an embodiment, the region scanned is the substrate **102** having fins **104**, as shown in FIG. **1**. In some examples, the region scanned is the substrate **102** having fins **104** where a metal gate is to be formed. It is contemplated that the region of interest can be any arbitrary location on a substrate, depending upon the application and/or process requirement. In addition, the substrate may be any suitable substrate having fins or trenches with an aspect ratio of about 3:1 or above. The scanning may be conducted by measuring a surface area of 500 nm×500 nm, or a different size of surface area of the substrate **102** with the scanning probes **120**, **202**, **204**, or **206**. The measured region may be any pixel resolution, for example 1024×1024, or 2048×2048, etc., depending upon the resolution needed for AFM images. A processor, such as the processor **134** of the control system **132** of FIG. **1**, may be used to control the AFM. The scanning may be performed in a manner as discussed in FIG. **3**A-**3**D or **4**A-**4**C to obtain AFM images of the fin in sub-nanometer resolution. The AFM images may include images of the fin **104** at different

depths from fin top to bottom, depending on the scanning probes used for the scanning and the effective measurement depth thereof.

At operation **504**, the AFM images of the fins **104** at a predetermined depth are selected to plot line edge profile of the fins. The predetermined depth may be in a range from about 1 nm to about 100 nm, which may vary depending upon the scanning probe used and the effective measurement depth thereof. In an embodiment where a conical scanning probe **202** is used to obtain AFM images, the predetermined depth can be in a range from about 5 nm to 30 nm, measuring from the top surface **107** of the fins **104**. The AFM images obtained within this range can have higher resolution since such range falls within the effective measurement depth D2 offered by the conical scanning probe **202**. FIG. **6**A illustrates an example of a top view of line edge profile **602** of the fins **104** at a predetermined depth of about 10 nm. In this example, a total of 19 fins **104** were captured by measuring a region measuring 500 nm×500 nm with a conical scanning probe, such as the scanning probe **202** of FIG. **2**, operating in a tapping mode along a longitudinal direction of the fins **104** at a travel distance of 0.5 nm. The line edge profile is then processed using any suitable software and processor-based system to show only the edge lines of the fins **104**, as shown in FIG. **6**B. In some embodiments, the edge lines may be leveled using a simple linear regression approach for ease of subsequent analysis. Since there were 19 fins (and each fin has two edge lines when viewing from top) plotted in FIG. **6**A, a total of 38 wiggling edge lines are shown in FIG. **6**B. For the sake of clarity, only the first two edge lines **604***a*, **604***b* representing one of the fins **104** are labeled.

At operation **506**, the edge lines of the fins at the predetermined depth are analyzed using a power spectral density (PSD) method to obtain spatial frequency data associated with the edge lines. The PSD method can decompose a waveform of each edge line (e.g., edge lines **604***a*, **604***b*) into long-period oscillations and short-period oscillations and plot the amplitude intensity (e.g., power strength) of these oscillation periods as a function of the spatial frequency through Fourier transformation. With PSD, the spatial frequency data associated with the edge lines can be obtained based on the amplitude intensity within spatial frequency ranges selected by the operator. The spatial frequency data can be used to obtain value corresponding to the LER of the fins. Knowing LER of the fins may be important to the process because effects of LER on FinFET performance have become more relevant in sub-45 nm technology nodes or below. It has been observed that the standard deviation of LER of the fins exceeding certain percentage (e.g., 5% or above) may negatively affect critical dimension of the subsequently formed metal gates, causing the gap-filling of the subsequent work-function metal layers to become non-uniform in thickness. As a result, the threshold voltage (V_{th}) of the metal gates can be compromised. The LER-induced variation is also found to be correlated with the short channel effect, which may reduce the surface mobility of the carriers. Analyzing the edge lines of the fins using PSD method allows the operator to obtain spatial frequency data of interest and determine LER profile of the fins.

At operation **508**, the spatial frequency data of the PSD is selected at interest of the operator to calculate LER profile of the fins. FIG. **7** is an example PSD plot **700** for the edge lines of FIG. **6**B according to some embodiments of the present disclosure. As indicated above, the PSD plot provides the amplitude of the oscillation periods (expressed in arbitrary unit) as a function of the spatial frequency. In the embodiment shown in FIG. **7**, the spatial frequency is associated with a predetermined wavelength of oscillations periods of the line edge profile, and the predetermined wavelength is in a range from about 1 nm to about 1000 nm. Spatial frequency is the inverse of the wavelength of the oscillation periods. For example, the PSD at the spatial frequency of 10 μm^{-1} or less in FIG. **7** will include all amplitude of the oscillation periods greater than 100 nm in wavelength, while the PSD at the spatial frequency of 100 μm^{-1} or greater will include all amplitude of the oscillation periods less than 10 nm in wavelength. Since the PSD represents the amplitude of the oscillation periods at a particular spatial frequency, an operator can use PSD plot to calculate the total amplitude of oscillation periods over a given range of wavelength by integrating total PSD within that spatial frequency range. The square root of the integrated value will yield RMS (root mean square), which is an indicator of roughness. With this approach, the operator may select the spatial frequency range of interest to calculate the line edge roughness (LER) of the fins, for example the LER of the fin top and/or region near the fin top, such as the region within the effective measurement depth of the scanning probes used for obtaining AFM images. As the device mobility can be affected by the line edge roughness of the fins, the spatial frequency range may be selected based on its correlation to the device mobility and in a range between about 1 μm^{-1} and about 1000 μm^{-1}, for example 10 μm^{-1} and 100 μm^{-1}. It is contemplated that this spatial frequency range is mere an example and may vary depending upon the application, or the requirement predetermined during the research and development stage.

The wavelength of the oscillation periods may be arbitrarily set based on the process, inspection and/or device requirements to extract spatial frequency data at interest of an operator. For example, the integrated value of PSD at the spatial frequency of, for example, 10 μm^{-1} or less (e.g., oscillation periods having a wavelength of 100 nm or above) may be referred to as low spatial frequency data, while the integrated value of PSD at the spatial frequency of, for example, 30 μm^{-1} or greater (e.g., oscillation periods having a wavelength of 33 nm or below) may be referred to as high spatial frequency data. The operator may purposely filter out or disregard high spatial frequency data due to the data being associated with excess noise from damping of the scanning probe or cantilever oscillation, or due to the data being identified as from the measurement region other than fin top or regions near the fin top (e.g., bottom region between the fins). In an embodiment shown in FIG. **7**, the PSD at a spatial frequency range of 10 μm^{-1} to 100 μm^{-1} is selected to calculate RMS for all oscillation periods having a wavelength in a range from about 100 nm to about 10 nm, which is highlighted by region **702**. This range of the oscillation period is selected because the edge lines of FIG. **6**B are found to have a prominent oscillation period in a range from about 25 nm to about 50 nm in wavelength. In most cases, the oscillation period may be considered prominent when the intensity of a particular oscillation period is greater than other oscillation periods by 2 times or above, for example 5 times to 10 times. The prominent oscillation period can be identified/calculated by a processor or a software using the Fourier transform or any suitable mathematical technique. It is contemplated that the operator may select other wavelength range of the oscillation periods to obtain LER at different regions along the longitudinal direction of the fins that may become an issue at a later stage. An example region that may become an issue to the process is the region(s)

where a distance between two adjacent edge lines (e.g., **604***a*, **604***b*) is less than a predetermined value (e.g., about 25 nm or below, for example in a range from about 10 to about 20 nm) which may negatively affect critical dimension of the subsequently formed metal gates, and thus, cause the device performance to suffer.

At operation **510**, the calculated LER (e.g., RMS for the spatial frequency data of interest) of the fins is compared to a reference LER (of the fins) to determine whether optimization or modification of the fin fabrication process is proceeded. The reference LER may be in a range from about 1 nm to about 10 nm, for example about 2 nm to about 5 nm, which may vary depending upon the application or device requirement. If the calculated LER is outside the range of the reference LER, or if standard deviation of the calculated LER exceeds certain percentage (e.g., 5% or above, for example about 10% or above) of the reference LER, the fin fabrication process may be modified, corrected, or optimized to produce fins with reduced LER. For example, the material properties of the photoresist, the mask roughness, and/or the process parameters of the patterning and/or etching processes used during the lithography for transferring features into the substrate for fabrication of fins may be modified or refined to adjust the LER profile of the fins. Alternatively or additionally, the linewidth of the fins may be adjusted to increase the mechanical strength of the fins, thereby reducing the LER of the fins. In any case, the LER measurement of the fins with an atomic force microscope of the present disclosure using the aforementioned surface roughness (RMS) and power spectral density (PSD) techniques can allow the manufacturer to help fabricate fins with reduced LER or less linewidth variations.

Various embodiments of this disclosure relate generally to a system and methods to determine line edge roughness of a substrate, such as fins of a FinFET device. A probe tip is employed to scan across the fins at target regions of the FinFET device to obtain line edge profile of the fins at the target regions. The line edge profile is then analyzed using a power spectral density (PSD) method to extract line edge roughness of the fins at desired spatial frequency domain. The line edge roughness of the fins can be used to refine or correct process so as to mitigate undesirable line edge roughness and/or linewidth variations. In some cases, the use of a cylinder-shaped AFM probe oscillating in vertical movement allows the probe to reach different depths below the fin top and be in close proximity to the bottom between the adjacent fins. Therefore, sub-nanometer resolution images of the fin top and regions near the fin top can be obtained. In addition, scanning the AFM probe tip in tapping mode can increase the imaging speed since it reduces the lateral forces exerted by the tip on the fin top, thereby reducing tip-fin top wear while providing prolonged tip lifetime.

In an embodiment, a method for measuring a characteristic of a substrate is provided. The method includes scanning over the substrate with a scanning probe microscope, the substrate having fins thereon, the scanning obtaining images showing respective fin top regions of the fins, the scanning probe microscope interacting with respective portions of sidewalls of the fins by a scanning probe oscillated during the scanning, selecting images obtained at a predetermined depth below the fin top regions to obtain a line edge profile of the fins, by a processor-based system, analyzing the line edge profile of the fins using power spectral density (PSD) method to obtain spatial frequency data of the line edge profile of the fins, and by the processor-based system, calculating line edge roughness of the fins based on the spatial frequency data.

In another embodiment, a method includes scanning a surface of the substrate with a scanning probe, the substrate having fins extended upwardly, the scanning obtaining images showing a line edge profile of the fins, the scanning probe using a spherical-shaped probe tip driven into vertical oscillation to engage with at least a portion of a sidewall of the fins during a series of interaction periods, by a processor-based system, analyzing the line edge profile of the fins using power spectral density (PSD) method to obtain spatial frequency data of the line edge profile of the fins, and by the processor-based system, calculating line edge roughness of the fins based on the spatial frequency data.

In yet another embodiment, a system is provided. The system includes a processor and a non-transitory computer readable medium connected to the processor. The non-transitory computer readable medium containing computer-executable instructions, which when executed by the processor, are operable to cause a scanning probe microscope to scan a surface of a substrate with a scanning probe, the substrate having fins extended upwardly, the scanning obtaining images showing respective fin top regions of the fins, the scanning probe interacting with respective portions of sidewalls of the fins by a spherical-shaped probe tip oscillated during a series of interaction periods, select images obtained at a predetermined depth below the fin top regions to plot a line edge profile of the fins, analyze the line edge profile of the fins using power spectral density (PSD) method to obtain spatial frequency data of the line edge profile of the fins, and calculate line edge roughness of the fins based on the spatial frequency data.

The foregoing outlines features of several embodiments so that those skilled in the art may better understand the aspects of the present disclosure. Those skilled in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments introduced herein. Those skilled in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions, and alterations herein without departing from the spirit and scope of the present disclosure.

What is claimed is:

1. A method for measuring a characteristic of a substrate, the method comprising:

scanning over the substrate with a scanning probe microscope, the substrate having three-dimensional structures thereon, the scanning obtaining images showing respective regions of the three-dimensional structures;

selecting images obtained at a predetermined depth below the regions to obtain a topographical feature profile of the three-dimensional structures;

by a processor-based system, analyzing the topographical feature profile of the three-dimensional structures using a power spectral density (PSD) method to obtain spatial frequency data of the topographical feature profile of the three-dimensional structures; and

by the processor-based system, calculating a topographical feature characteristic of the three-dimensional structures based on the spatial frequency data.

2. The method of claim 1, further comprising:
modifying a three dimensional structure fabrication process based on the calculated topographical feature characteristic.

3. The method of claim 1, wherein the scanning probe microscope is an atomic force microscope (AFM).

4. The method of claim 1, wherein the scanning is performed at one or more target regions where a metal gate is to be formed over the three dimensional structures.

5. The method of claim 1, wherein the scanning is performed by measuring a 500 nm×500 nm or larger region of the substrate with the scanning probe.

6. The method of claim 1, wherein the predetermined depth is in a range from greater than about 0 nm to about 80 nm.

7. The method of claim 1, wherein the scanning is operated in a tapping mode along a longitudinal direction of the three-dimensional structures.

8. The method of claim 1, further comprising the scanning probe microscope interacting with respective portions of sidewalls of the three-dimensional structures by a scanning probe oscillated during the scanning, wherein the spatial frequency data is associated with a predetermined wavelength of oscillations periods of the line edge profile, and the predetermined wavelength is in a range from about 1 nm to about 1000 nm.

9. A method for measuring a surface of a substrate, the method comprising:
scanning a surface of the substrate with a scanning probe, the substrate having three-dimensional structures extended upwardly, the scanning obtaining images showing a topographical feature profile of the three-dimensional structures, the scanning probe using a probe tip driven into oscillation to engage with at least a portion of a sidewall of the three-dimensional structures during a series of interaction periods;
by a processor-based system, analyzing the topographical feature profile of the three-dimensional structures using a power spectral density (PSD) method to obtain spatial frequency data of the topographical feature profile of the three-dimensional structures; and
by the processor-based system, calculating a topographical feature characteristic of the three-dimensional structures based on the spatial frequency data.

10. The method of claim 9, wherein the scanning probe has a spherical shaped probe tip and a conical sidewall extending in a direction at a first angle with respect to a longitudinal axis of the scanning probe, wherein the first angle is in a range of about 1° to about 20°.

11. The method of claim 9, wherein the scanning probe has a spherical shaped probe tip and a straight sidewall parallel to a longitudinal axis of the scanning probe.

12. The method of claim 9, wherein the scanning probe has a diameter less than a three-dimensional structure to the three-dimensional structure spacing between neighboring pairs of the three-dimensional structures.

13. The method of claim 9, wherein the scanning is operated in a tapping mode along a longitudinal direction of the three-dimensional structures.

14. The method of claim 9, wherein scanning a surface of the substrate with a scanning probe is performed in an environmentally controlled chamber in which the moisture is under 0.5 ppm and oxygen is under 1 ppm.

15. The method of claim 9, further comprising:
by the processor-based system, determining a spatial frequency range based on an oscillation period of the topographical feature profile, and the topographical feature characteristic of the three-dimensional structures is calculated based on the spatial frequency data in the spatial frequency range.

16. A system, comprising:
a processor; and
a non-transitory computer readable medium connected to the processor, the non-transitory computer readable medium containing computer-executable instructions, which when executed by the processor, are operable to:
cause a scanning probe microscope to scan a surface of a substrate with a scanning probe, the substrate having three-dimensional structures extended upwardly, the scanning obtaining images showing respective regions of the three-dimensional structures, the scanning probe interacting with respective portions of sidewalls of the three-dimensional structures by a probe tip oscillated during a series of interaction periods;
select images obtained at a predetermined depth below the regions to plot a topographical feature profile of the three-dimensional structures;
analyze the topographical feature profile of the three-dimensional structures using power spectral density (PSD) method to obtain spatial frequency data of the topographical feature profile of the three-dimensional structures; and
calculate a topographical feature characteristic roughness of the three-dimensional structures based on the spatial frequency data.

17. The system of claim 16, wherein the computer-executable instructions, when executed by the processor, cause the processor to compare the calculated topographical feature characteristic of the three-dimensional structures with a reference topographical feature characteristic to determine if a modification to a three-dimensional structure fabrication process is to be proceeded.

18. The system of claim 16, wherein the computer-executable instructions, when executed by the processor, cause the scanning probe microscope to operate in a tapping mode along a longitudinal direction of the three-dimensional structures.

19. The system of claim 16, wherein the predetermined depth is in a range between about 0 nm and about 80 nm.

20. The system of claim 16, wherein the spatial frequency data is associated with a predetermined wavelength of oscillations periods of the line edge profile, and the predetermined wavelength is in a range between 1 nm and 1000 nm.

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